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Towards a revised combination formula for practical calculations of potential and actual evaporation I. Daytime evaporation in non-advective conditions.

by N Thompson

1. Introduction The combination formula is written conveniently in the form

$$\lambda E = \frac{\Delta'(R_N - G) + \rho c_p \delta q / r_a}{\Delta' + c_p(1 + r_s/r_a)/\lambda} \qquad (1.1)$$

where $\Delta' = \partial q(sat)/\partial T$

$q(sat)$ = saturation specific humidity

δq = specific humidity deficit

r_a = resistance to transfer of heat and water vapour from mean source height in canopy to height at which δq is measured.

The bulk stomatal resistance of the crop canopy (r_s) is defined usually on the assumption that the roughness lengths for vertical transfer of momentum, heat and water vapour to or from the canopy are equal, or equivalently, that the mean heights within the canopy where these fluxes originate, or are observed, are the same. Momentum however may be transferred to the underlying surface by pressure forces as well as skin friction and so the canopy's momentum sink is at a greater height than the sources of heat and water vapour. If the canopy is dense so that negligible heat or moisture transfer occurs at the soil surface then the roughness lengths for heat and moisture transfer (z_T , z_q) are approximately equal and about one fifth that for momentum transfer (z_o) (Thom 1975). Monteith (1973) showed that the error in calculating r_s without allowing for the additional resistance to heat and water vapour transfer is approximately

$$\delta r_s = r_s' - r_s = \frac{4}{u_*}\left(\frac{\Delta'}{c_p} \cdot \frac{H}{E} - 1\right) \qquad (1.2)$$

where r_s' = "true" bulk stomatal resistance

Typical values for u_* over grass ($z_o \sim 0.01$ m) and cereals ($z_o \sim 0.1$ m) in near-neutral conditions with 10 m winds of 2 and 5 ms^{-1} are respectively 0.12, 0.29 and 0.17, 0.43 ms^{-1}. For a well-watered crop growing in summer conditions $H/\lambda E$ is around 0.3 and Δ/γ is about 2 and so in these cases δr_s ranges from about -13 to -4 sm^{-1}. r_s therefore does not represent satisfactorily the stomatal resistance of the whole canopy because it includes a significant and variable contribution resulting from the incorrect definition of the roughness length for heat and water vapour transfer. Manipulations of Eq (1.1) in the remainder of this memorandum will use therefore values of r_a calculated for $z_{T,q} = 0.2\, z_o$, and r_s' instead of r_s.

2. Minimum bulk stomatal resistance Bulk stomatal resistances have been calculated by most investigators as r_s rather than r_s' and have some dependance on wind speed therefore. Minimum values occur in crops which are well illuminated, freely supplied with water and subject to only small deficits of specific humidity. Table 1 gives some values which have been obtained from measurements over various mature crops (the problem of poorly-illuminated crops which may also be immature and covering only partly a wet soil is discussed later).

Table 1 Typical minimum values for r_s for mature crops

Crop	r_s (min) sm^{-1}	Reference
Pine Forest	100	Stewart and Thom 1973
Lucerne	25	Stern and Donald 1962
Potatoes	45	Szeicz et al 1969
Beans	30	Linacre et al 1964
Cotton	30	Linacre et al 1964
Barley	30	Monteith et al 1965
Barley	30	Grant 1975
Barley	30	Russell 1979
Grass and Clover	25	Szeicz and Long 1969
Pasture	40	Russell 1979
Sugar beet	20 (r_s')	Brown and Rosenberg 1973

Table 1 suggests that the corrected bulk stomatal resistance r_s' (min) for cereals is probably around 20 sm^{-1}. A satisfactory value for potatoes is say 35 sm^{-1}. r_s' for lush pasture is probably similar to that for cereals, but for most grazed or periodically-cut pasture the green leaf area issignificantly less than that for mature cereals so that a value for r_s' (min) of around 30 sm^{-1} is probably more appropriate for this vegetation.

3. Effects of specific humidity deficit on bulk stomatal resistance It is well known that high evaporative demand associated with large specific humidity deficits leads to partial stomatal closure and hence increase of r_s' (eg Jarvis 1976). This leads to a corresponding reduction in potential evaporation. When

significant soil moisture deficits exist so that the evaporation is non-potential the effects of high evaporative demand are likely to be proportionally larger than in the potential case. Published data on the effects of humidity deficit on r_s appear to be almost completely lacking for arable crops. Measurements on Sitka spruce needles by Watts (1977) showed the reciprocal of needle stomatal resistance decreasing linearly to about 35% of its maximum value when specific humidity deficit increased from zero to about 0.007. There have been numerous studies of the bulk stomatal resistance of well-watered field crops which show this resistance increasing rapidly during the afternoon on days with high evaporative demand well before the time when significant stomatal closure due to decreasing light intensity occurs (§ 4). As yet there is insufficient evidence to say whether the premature closure in these cases was caused solely by shortage of water in the leaf tissues rather than being due at least in part to a high vapour pressure deficit: for convenience the latter interpretation will be pursued here.

The humidity deficit in the crop ($\delta q'$) is not usually the same as δq (deficit at screen level) but rough relationships between the two quantities may be obtained by an iterative application of the combination formula (Thompson 1978a). Over smooth surfaces (z_o = 0.01 m) in light winds (say $U_{10} \leq 5$ ms^{-1}) the calculated maximum canopy deficit is less than 0.003 for a screen deficit of 0.010, even for net radiation as high as 400 Wm^{-2}, and with winds as high as 10 ms^{-1} does not exceed 0.004 (in each case r_s' = 20 sm^{-1}). For a rougher surface (z_o = 0.10 m) the maximum values are somewhat larger, around 0.004 at 5 ms^{-1} and about 0.005 at 10 ms^{-1}. Thus for most summer conditions when net radiation is unlikely to exceed about 400 Wm^{-2} and winds over taller vegetation (height ~ 1 m) are seldom more than 5 ms^{-1} the in-canopy deficits in unstressed crops are probably small enough to have little direct effect on bulk stomatal resistance. Similar calculations for slighly stressed crops (or for sparser crops where leaf area index is considerably less than the 6 or so expected with dense crops) with r_s' assumed to be 60 sm^{-1}, show the in-crop deficits becoming larger. Here for example with high net radiation (200-400 Wm^{-2}) the deficits in screen and crop are nearly the same over tall crops in the stronger winds ($U_{10} \sim$ 10 ms^{-1}) and even over short crops will generally exceed .005 in winds of 5 ms^{-1} at these radiation levels. The stressed plant therefore will be subjected to a higher humidity deficit than unstressed plants, by an amount depending to some extent on plant water deficit. In the present situation with its paucity of physiological data it is profitless to attempt to derive an exact expression for the response of r_s' to δq but remembering that plants suffering from a soil moisture deficit appear to be especially liable to premature stomatal closure due to high evaporative demand then an expression of the form

$$r_s' = r_s'(\min)(LAI)\left(1 + \frac{r_s'(\delta q=0) - r_s'(\min)(LAI)}{r_s'(\min)(LAI)}\left(1 + \alpha \delta q\right)\right) \qquad (3.1)$$

will probably suffice for the moment. Here r_s' (δq = 0) is the bulk stomatal resistance of the canopy including corrections for intensity of incident radiation, leaf area index (LAI) and soil moisture deficit: in optimal conditions its minimum value will be r_s' (min) (LAI). α will vary with crop type and strictly with other variables as well, such as LAI, wind speed and net radiation but with the present lack of physiological data a constant value of 100 will be assumed. Thus a mature barley crop (r_s' (min) = 20) under some stress would have its bulk resistance increased from say 60 sm^{-1} to 80 sm^{-1} at a specific humidity deficit (δq) of .005. In the case of a more highly stressed crop

(r_s' (δq = 0) = 100 sm^{-1}) this humidity deficit would increase r_s' to 140 sm^{-1}.

4. Effects of leaf area index and light intensity on bulk stomatal resistance Leaf area indices of autumn-sown cereals are small throughout the winter so that this crop can transpire only small amounts of water until the major spurt in leaf-growth which occurs in spring. Biscoe et al (1978) give some results for Huntsman wheat drilled before the mild winter of 1974/75 which had achieved a leaf area index of 0.5 by around mid-March, with a rooting depth by then of 0.8 m. A similar LAI was found for autumn-sown Capelle Desprez by the following mid-March (Watson et al 1963). The date of spring-sowing varies with latitude and the field situation but is typically around mid-March in southern districts. These latter sowings achieve an LAI of around 0.5 some 40 to 50 days after sowing and thereafter the LAI will double roughly every 10 days, with a dense cover by about the beginning of June. Cold springs will delay germination and leaf development, and extend the period between sowing and dense leaf development (LAI ~ 6) by about a fortnight. Autumn-sown cereals reach these high LAI's earlier than the spring crops, by around a fortnight and already have leaf area indices of around 1 when spring sowings have scarcely reached brairding. Development of leaf area of the winter cereals is usually little affected by soil moisture deficits which become substantial rather later in the season. In fact a closely linear correlation has been found between leaf extension rate and temperature, down to temperatures at least as low as 3 deg C (Biscoe and Gallagher 1977) and this suggests that, provided simple relations between extension rate and rate of increase of leaf area can be found, and also between leaf formation rate and temperature, then it should be possible to estimate the number of days to reach particular leaf area indices for any spring pattern of temperature. Such a study is beyond the scope of the present paper, but is expected to be begun shortly and reported in an Agricultural Memorandum.

Time of onset of senescence is a function of early summer temperature and possibly soil moisture deficit. Autumn-sown cereals will begin to senesce during June and decline rapidly in July to negligable (green) LAI's before the end of the month. Senescence of the spring-sown crops is delayed by a fortnight or so, with very small LAI's by early August. High temperatures in the growing season cause early senescence and vice-versa, so that the date of final senescence may vary by at least a month.

Pasture maintains of course a significant green leaf area index throughout the year, although winter LAI's will be smaller than summer values - say around 2 rather than 4 or more for summer.

Sowing dates for potatoes vary widely with variety and locality but for a typical maincrop tuber planted early in May, the LAI remained negligable until the beginning of June and then increased steadily to a maximum in the latter part of July (Dyson 1965). LAI declined to small values by late September. Other studies by Bremner and Taha (1966) showed a similar behaviour for the first part of the growing cycle but then a much more rapid decline to small values by the end of August. Potatoes however are more responsive to SMD than cereals because of fairly shallow rooting (~ 0.6 m) and early senescence is more likely to depend on SMD than for the cereals.

Roughly linear relations have been found between stomatal resistances of single cereal leaves not under water stress and incident solar radiation. For barley Biscoe et al (1977) describe results fitted roughly by the relation

$$\frac{1}{r_{sL}} = 0.002 + 0.000023\, R(s) \qquad ms^{-1} \qquad (4.1)$$

where $R(s)$ is the incident solar radiation in Wm^{-2} and r_{sl} is the stomatal resistance per unit area of epidermis. Monteith et al (1965) made measurements on barley which were fitted by

$$\frac{1}{r_{sl}} = 0.005 + 0.000008\ R(s) \qquad (4.2)$$

For wheat Denmead (1976) gives a relation in terms of net radiation absorbed by the leaves which may be converted roughly to

$$\frac{1}{r_{sl}} = 0.000014\ R(s) \qquad (4.3)$$

Although not explicit in Denmead's article it appears that his conductances (1/resistance) should be halved as they refer apparently to the sum of conductances of both leaf surfaces. On this basis his results give much lower conductances at lower light levels than the other two sets.

For other species (e.g. sorghum, maize) Turner (1974) found hyperbolic relationships between resistance and light intensity (Biscoe et al's and Monteith et al's data could be fitted also by hyperbolic relations by smoothing to zero conductance at negligable irradiances - in either case the authors presented no data at irradiances lower than about 30 Wm^{-2}). The author is not aware of similar data for pasture or field crops such as potatoes, though it is probably reasonable to assume some sort of hyperbolic variation with irradiance for these species also.

In practice the behaviour of leaf conductance at low light intensities is probably not very important for the spring cereals and potatoes where significant transpiration will occur usually only in the period say April to July (cereals) or August (potatoes) where daytime light intensities are relatively large. The autumn-sown cereals with their leaf area index of 0.5 by about mid-March will show some effects of low light intensity on stomatal opening, particularly in the winter; however even as late as mid-February the LAI will only be about 0.25, with a corresponding minimum bulk stomatal resistance of around 200 sm^{-1}, or 10 times larger than the summer values, and so transpiration at these times will be small. The situation is rather different for pasture which will maintain a significant green leaf area index throughout the winter as well as the summer half of the year, but here data on the response of leaf conductance to light intensity are lacking. The point is of some importance in the calculation of winter transpiration since the higher average wind speeds which occur then will produce relatively large transpiration when low radiation levels and perhaps low temperature combine to produce restricted stomatal opening.

Data of Monteith et al (1965) for a barley canopy support roughly a relation for minimum bulk stomatal resistance of the form

$$\left.\begin{aligned} r_s'(min) &= \frac{r_{sl}(min)}{L} \qquad (L \leq 6) \\ &= \frac{r_{sl}(min)}{6} \qquad (L > 6) \end{aligned}\right\} \qquad (4.4)$$

At lower light intensities the following relations fit roughly the results of Monteith et al:

$$r_s' = \frac{120}{L_o(1.1+0.0018R(s))} \cdot \frac{1}{\left(1+(L_1-1)\frac{(R(s)-1.5(0.01R(s))^3)}{800}\right)} \quad (R(s) \geqslant 60\ Wm^{-1}) \quad (4.5)$$

where (LAI $\geqslant$ 1): $L_o = 1$

L_1 = LAI (up to a maximum value of 6)

(LAI < 1): L_o = LAI

$L_1 = 1$

$$r_s' = \frac{6000}{L_2 \cdot R(s)} \quad (R(s) < 60\ Wm^{-2}) \quad (4.6)$$

where $L_2 = 1$ (LAI $\geqslant$ 1)

= LAI (LAI < 1)

Eq (4.5) uses Eq (4.2) and (4.4), modified to allow for the progressively greater stomatal closure in the lower parts of denser canopies as light intensity increases. At irradiances of less than 60 Wm^{-2} it is assumed that radiation is too weak to open the stomata of more than the top layer of the canopy. It will be assumed that relations (4.5) and (4.6) apply to pasture and other field crops. In the case of senescing canopies the relations may still be applied, provided that LAI is the total leaf area index and the resulting canopy resistances are multiplied by the ratio of total to green leaf area index.

5. Effects of soil moisture deficit on bulk stomal resistance The tradition within the Meteorological Office has been to estimate actual transpiration in cases where a soil moisture deficit (SMD) exists by first calculating the potential transpiration on the assumption that the soil moisture deficit is small enough to have negligible effect, and then correcting P.E. by an empirical factor which is a function of soil moisture deficit. This is clearly an unsatisfactory procedure, first because of its lack of directness and secondly because variables such as δq, T, U and even R_N would all have been different had the crop been freely transpiring. Thus stressed vegetation is hotter than the unstressed crop with consequent increases in δq and U, and decrease in R_N. In fact the utility of the very concept of "potential transpiration" is in doubt: it is not the transpiration which would have been observed had the vegetation been freely supplied with water, for the reasons given above. Equally it is not the quantity required to assess irrigation need though here the problem is confounded by the difficulty of assessing the effects on transpiration of advection of energy from surrounding semi-arid areas: unfortunately meteorological data on which irrigation assessment is based usually come from instruments exposed over these drier areas.

Russell (1979) using estimates of rates of evaporation from barley and pasture which were calculated from rainfall and changes in soil moisture content (neutron probe, with correction for drainage), obtained relations between r_s and SMD which in principle allow actual evaporation to be calculated directly. Russell's values differed significantly for the two sites at which the barley was grown even though soil type was the same: on one site however which was further from the weather station r_s was calculated only monthly, rather than 10-daily at the other site.

Using only results for barley where the green leaf area index was large he found that $r_s \simeq 30$ sm^{-1} for SMD's up to about 30 mm, and then rose at a rate of about 1.5 sm^{-1} for each mm increase in SMD (average from both sites). For pasture, $r_s \simeq 40$ sm^{-1} up to an SMD of 40mm, increasing by about 1sm^{-1} per mm SMD up to 75 sm^{-1} and about 3 sm^{-1}/mm above 75 mm. No data were available for SMD's above 100mm. However the scatter was large and the differences in behaviour of r_s for barley and pasture at higher SMD's could probably be ignored. The figures may be interpreted as giving minimum values for r_s' for barley of around 20 sm^{-1}, and 30 sm^{-1} for pasture, with an overall behaviour approximated by

$$r_s'(1) = \begin{matrix}20 \text{ (barley)} \\ 30 \text{ (pasture)}\end{matrix} \qquad 0 < \text{SMD} < 35 \qquad (5.1.1)$$

$$r_s'(2) = r_s'(1) + 1.5\,(\text{SMD}-35) \qquad 35 < \text{SMD} < 100 \qquad (5.1.2)$$

$$r_s'(3) = r_s'(1) + 100 + 2\,(\text{SMD}-100) \qquad 100 < \text{SMD} < 130 \qquad (5.1.3)$$

$$r_s'(4) = \infty \qquad \text{SMD} > 130 \qquad (5.1.4)$$

The usual assumption is made that any rain reduces r_s' to its value $r_s'(1)$ until it has been evaporated, whereupon r_s' returns to the value appropriate to the SMD.

Grant (1975) found for barley growing in a medium soil the relations

$$r_s(1) = 20 \qquad 0 < \text{SMD} < 40 \qquad (5.2.1)$$

$$r_s(2) = 20 + 1.2\,(\text{SMD}-40) \qquad \text{SMD} > 40 \qquad (5.2.2)$$

The differences between Eq (5.1) and (5.2) are those to be expected when the scatter in the data from which they were derived is taken into account.

Rough allowances can be made for "heavy" and "light" soils (with more, or less water-holding capacity than medium soils) by adjusting the relations given above to

$$r_s'(1)\,(\text{heavy}) = \begin{matrix}20 \text{ (barley)} \\ 30 \text{ (pasture)}\end{matrix} \qquad 0 < \text{SMD} < 50 \qquad (5.3.1)$$

$$r_s'(2)\,(\text{heavy}) = r_s'(1)\,(\text{heavy}) + 1.5\,(\text{SMD}-50) \qquad 50 < \text{SMD} < 125 \qquad (5.3.2)$$

$$r_s'(3)\,(\text{heavy}) = r_s'(1)\,(\text{heavy}) + 115 + 2\,(\text{SMD}-125) \qquad 125 < \text{SMD} < 175 \qquad (5.3.3)$$

$$r_s'(4)\,(\text{heavy}) = \infty \qquad \text{SMD} > 175 \qquad (5.3.4)$$

$$r_s'(1)\,(\text{light}) = \begin{matrix}20 \text{ (barley)} \\ 30 \text{ (pasture)}\end{matrix} \qquad 0 < \text{SMD} < 25 \qquad (5.4.1)$$

$$r_s'(2)\,(\text{light}) = r_s'(1)\,(\text{light}) + 1.5\,(\text{SMD}-25) \qquad 25 < \text{SMD} < 60 \qquad (5.4.2)$$

$$r_s'(3)\,(\text{light}) = r_s'(1)\,(\text{light}) + 55 + 3\,(\text{SMD}-60) \qquad 60 < \text{SMD} < 100 \qquad (5.4.3)$$

$$r_s'(4)\,(\text{light}) = \infty \qquad \text{SMD} > 100 \qquad (5.4.4)$$

In the case of wheat it will be assumed that Eq (5.1), (5.3) and (5.4) may be used, in the versions given for barley. The other field crop which will be considered now is potato. Smith (1973) presents results which will be used here. He noted that early in the season a major check in transpiration at relatively small SMD's may occur, due presumably to still-restricted development of the root structure (even when fully grown the roots are only assumed to extend to a nominal depth of 0.6 m). This complication will be ignored here in order to produce the following simplified relations for mature crops.

$r_s'(1)$ (medium) = 35 $\quad 0 < SMD < 35$ (5.5.1)

$r_s'(2)$ (medium) = 35 + 15 (SMD-35) $\quad 35 < SMD < 60$ (5.5.2)

$r_s'(3)$ (medium) = ∞ $\quad SMD > 60$ (5.5.3)

$r_s'(1)$ (heavy) = 35 $\quad 0 < SMD < 50$ (5.6.1)

$r_s'(2)$ (heavy) = 35 + 10 (SMD-50) $\quad 50 < SMD < 80$ (5.6.2)

$r_s'(3)$ (heavy) = ∞ $\quad SMD > 80$ (5.6.3)

$r_s'(1)$ (light) = 35 $\quad 0 < SMD < 25$ (5.7.1)

$r_s'(2)$ (light) = 35 + 20 (SMD-25) $\quad 25 < SMD < 45$ (5.7.2)

$r_s'(3)$ (light) = ∞ $\quad SMD > 45$ (5.7.3)

All the equations (5) may be modified and applied to equations (4.5) and (4.6) to produce bulk stomatal resistance of crops under water stress: the modification involves rewriting Eq (5) to give the ratio $\frac{r_s'(\text{stressed})}{r_s'(\text{min})}$ for the assumed dense, well illuminated crop, and then multiplying the values given by Eq (4.5) or (4.6) by this ratio.

6. Corrections for the effects of incomplete crop cover At the early stages of the growth of a crop when the leaf area (LAI) is small ($\ll 1$) nearly all the water vapour transport from the surface takes place from the bare soil. The drying process may be approximated by two stages (Ritchie 1972): Stage 1 where the rate of evaporation is limited only by the evaporation demand of the atmosphere (sometimes called a "constant rate" stage) and Stage 2 ("falling rate" stage) where water movement to the evaporation sites near the surface is controlled increasingly by the soil's hydraulic properties. With increasing leaf area index the evporative demand of the atmosphere is used increasingly in transpiration, but the two stages described above may be used to define still the evaporation from the soil surface, at a rate which has been decreased suitably to allow for interception of radiation by the plant canopy.

The albedo of the soil/canopy surface (ϵ) may be approximated by

$$\epsilon = \epsilon_s + 0.17(0.25 - \epsilon_s).LAI \qquad (6.1)$$

($0 \leq LAI \leq 6$), where ϵ_s is the albedo for bare soil (~ 0.1 when wet increasing to ~ 0.3 when dry) and for a full canopy is assumed to be 0.25. Use of Eq (6.1) with a suitable empirical radiation formula allows the net radiation above the canopy (R_N) to be estimated (e.g. Thompson 1978a).

Stage 1 evaporation takes place at a roughly constant rate until say X mm of water are evaporated (it is assumed that the evaporative process begins with the soil at field capacity). Stage 2 evaporation then follows an equation of the form

$$Y = \mu t^{1/2} \qquad (6.2)$$

provided the evaporation demand is constant (Ritchie 1972): here Y is the total evaporation from the onset of stage 2 phase, and μ is a constant which (like X) depends on the soil properties. Eq (6.2) is not always well suited to UK calculations, where the evaporative demand of the atmosphere may show large

fluctuations. A more appropriate relation for both stages of evaporation is then of the form

$$E = \mu_i . E(SMD=0) \qquad i = 1, n \qquad (6.3)$$

where $n \sim 3$. i (and hence μ) changes with increments of water storage of Y_i mm, where Y_i is a function of soil type. Table 6.1 gives values of μ and Y which were suggested by Smith (1973). It is assumed for convenience that

Table 6.1 Empirical constants for evaporation from bare soil (after Smith 1973)

	Soil Water Storage		
	High	Medium	Low
Capacity of layer 1	25 mm	25 mm	25 mm
μ_1	1.0	1.0	1.0
Capacity of layer 2	10 mm	8 mm	1 mm
μ_2	0.5	0.3	0.1
Capacity of layer 3	5 mm	2 mm	-
μ_3	0.1	0.1	-

stage 1 evaporation tables place from an uppermost soil layer, and stage 2 evaporation from 1 or 2 layers beneath. Any rainfall is assumed to wet the soil from the top layers downwards and be evaporated at the full rate until the SMD in the top layer again reaches 25 mm. Smith noted that heavy clay soils crack when drying out so that rapid, deep percolation occurs during re-wetting. He suggested that the deep percolation was equal to about 65% of the difference between rainfall and evaporation.

Smith's suggestion that 25 mm may be extracted from all bare soils at the full potential rate is not in accord with Ritchie's data for a range of soil types. Ritchie's results are more in line with stage 1 drying limits of around 15, 10 and 5 mm for the three soil water storages. However, as Denmead and Shaw (1962) have pointed out, the drying process for a bare, initially wet, soil cannot be described strictly in terms of "constant" and "falling-rate" stages because the process depends on the evaporation demand of the atmosphere. For a low evaporative demand the evaporation will continue as close to the potential rate until (for medium or heavy soils) around 25 mm has been extracted when the drying rate falls sharply. However for high evaporative demands the check in the drying rate will occur earlier. It is suggested therefore that the coefficients in Table 6.2 be used rather than those in Table 6.1 since they should give a better estimate of summer evaporation, when the evaporative demand is often high. It is often convenient to use instead of the results in Table 6.2 roughly equivalent exponential functions of surface resistance

Table 6.2 Suggested empirical constants for evaporation from bare soil

	Soil Water Storage		
	High	Medium	Low
Capacity of layer 1	15	10	5
μ_1	1.0	1.0	1.0
Capacity of layer 2	10	10	10
μ_2	0.3	0.3	0.3
Capacity of layer 3	10	5	5
μ_3	0.1	0.1	0.1

(r_{ss}): the approximate relations are:

$$\left.\begin{aligned} r_{ss}\ (\text{light}) &= 100 \exp (0.20 \times SMD) \\ r_{ss}\ (\text{medium}) &= 100 \exp (0.14 \times SMD) \\ r_{ss}\ (\text{heavy}) &= 100 \exp (0.10 \times SMD) \end{aligned}\right\} \quad (6.4)$$

: the minimum resistance of 100 sm^{-1} is that given by Grant (1975) for wet soil. The soil moisture deficit (SMD) is assumed to fall to zero as soon as rain falls, and to return to its previous value when the rain has evaporated.

It is cumbersome to estimate evapotranspiration by calculating separately evaporation from the soil and transpiration from foliage and so following Grant (1975) a bulk canopy/ soil resistance is obtained by summing in parallel the soil and canopy contributions:

$$\frac{1}{r_s'(\text{total})} = \frac{I}{r_{ss}} + \frac{1}{r_s'} \quad (6.5)$$

Here r_s' is the canopy resistance adjusted for leaf area index, soil moisture deficit, evaporative demand and light intensity. Grant suggests that I may be equated to the fraction of (net) radiation transmitted by the canopy although this is unlikely to be more than a very rough approximation. However as long as I decreases fairly rapidly with LAI then the errors involved in using (6.5) are unlikely to be large. Denmead (1976) suggests that

$$I = \exp(-l.\ LAI) \quad (6.6)$$

Results discussed by Ritchie (1972) support a value for l of around 0.4 but Denmead shows how it varies with solar elevation and for a cereal crop gives typical values a few hours either side of midday of around 0.6. An average value of 0.5 will be assumed for the crops now being discussed.

The combination of soil and canopy resistances expressed by Eq. (6.5) becomes increasingly hard to justify as crop height increases. This is because the conventional calculation of the aerodynamic resistance used in the combination equation treats the average source height of transpired water as being in the upper part of the canopy: the resistance to transfer of soil moisture must be

larger than this. In practice in those circumstances where soil moisture does contribute substantially to the total evapotranspiration (low crop with small LAI) it is acceptable to use the same value of r_a for each transfer pathway. When LAI becomes larger the flux of water vapour from the soil will be small compared with transpiration and while the concept of a single (joint) aerodynamic resistance is fundamentally unsatisfactory it will lead to small errors only.

7. Net Radiation Relations used to calculate the net radiation are given in the Appendix. An allowance is made for the annual variation of the solar constant. The downward component of long-wave radiation for clear skies is calculated following Swinbank (1963). A long-wave emissivity of 0.95 is assumed for the surface. Crop-covered surfaces are assumed to have an albedo of 0.25. The albedo of bare soil is made to change progressively with increasing SMD from 0.1 when wet, to 0.3 when the SMD of the upper layers increase to (5, 10, 15 mm) for (light, medium, heavy) soils.

8. Soil heat flux This is estimated using the expressions given by Thompson (1979). An allowance is made for leaf area index when calculating daytime values, but nightime values are assumed to be independent of crop cover.

9. Interception and evaporation of rain or dew The maximum interception capacity of vegetation after dripping and stemflow has ceased is about 0.15-0.4 × LAI (mm) (e.g. Merriam 1961). Values for field crops (including grass) are probably around 0.2 × LAI. Interception and wetting studies (Courturier and Ripley 1973) show that rain is intercepted more or less fully until nearly one half of this capacity is reached, but thereafter the approach to full wetting is slower - a rough working rule is that about one third of the rain is intercepted in the latter half of crop wetting. It is assumed usually that the canopy resistance is zero while intercepted water is being evaporated. Such an assumption will be made here also for computational reasons, but in practice transpiration and evaporation of intercepted water (and evaporation from the soil) will often take place together during the day, especially when the uppermost leaves in the canopy become dry. At night dew may form, again with zero canopy resistance when it occurs; there may still be evaporation from the underlying soil but this water vapour will be intercepted by the canopy when dew occurs.

10. Nocturnal applications of the combination formula in light winds Equation (1.1) suggests that maximum rates of condensation of water onto foliage occur when r_a is very large, when winds are very light. In these circumstances the vertical turbulent mixing above the canopy is small and after an initial rapid deposition of dew the rate of deposition may fall off as the surplus water in the vicinity of the foliage is exhausted. This complication will be ignored and the rate of dew formation will be found by putting $r_s = 0$ in Equation (1.1). On clear nights the largest negative values of available energy may exceed 30 Wm^{-2}, and if winds are very light the rate of dew formation may reach about 0.06 mm hr^{-1}.

11. The representivity of measurements above the surface The basic meteorological variables from which evapotranspiration has to be calculated are screen temperature and humidity (measured at a height of about 1.2 m), wind speed (at 2 m or 10 m) and bright sunshine. Observations of the first three may be available hourly but in most cases will be measured only once a day (max and min temperature, 0900 dewpoint, 24-hour run of wind). There are possibilities of applying empirical corrections to once-daily data in order to obtain separate estimates of daytime and nighttime means (e.g. Wright 1978), and it may be possible to incorporate these ideas into an operational scheme eventually. For the present the usual assumption will be made that day- and nighttime temperatures are both given by

$$TA(\text{NIGHT}) = TA(\text{DAY}) = 0.5\left(TA(\text{MAX}) + TA(\text{MIN})\right) \qquad (11.1)$$

Specific humidities are equated to the value at 0900. Strictly a distinction should be made between day- and nighttime wind speeds, especially when measured at 2 m height where diurnal variations are larger than at 10 m. However, pending an extension of Wright's work to various locations around the United Kingdom, and to 2 m as well as 10 m winds, it will be assumed that day- and nighttime speeds are the same.

The standard observations just discussed will have been made over short grass, but often at a site which is poorly exposed, resulting in higher daytime and lower nighttime temperatures than at well-exposed sites and (more seriously) significantly underestimated wind speeds, particularly when obtained at 2 m height. These deficiences have to be acceptedbut a further difficulty is encountered when applying the data to the field situation, where the underlying surface may have very different characteristics from the short grass of the instrument enclosure. This point was touched upon by Thompson (1978b) who distinguished between the conversion of the meteorological data to a common reference height over short grass, and application of these data to a site with different surface roughness (and perhaps very different energy partition if irrigated). A simplifying assumption is needed now to make progress, and it will be that provided all data are corrected to say 20 m height initially they may be used then to calculate evaporation over any other surface simply by changing the roughness length from that for short grass (say 0.01 m) to that appropriate to the underlying crop. Thompson's Table 5 suggests that in the case of wind speed this is only a reasonable approximation (within about 15%) for very light winds, or with high available energy when winds are stronger.

12. Conversion of data to 20 m height and calculation of r_a. The treatment has been outlined by Thompson (1978b). The necessary equations are

$$\frac{U(z_1)}{U(z_2)} = \frac{\ln\left(\frac{z_1-d}{z_o}\right) - \psi_M\left(\frac{z_1-d}{L}\right)}{\ln\left(\frac{z_2-d}{z_o}\right) - \psi_M\left(\frac{z_2-d}{L}\right)} \qquad (12.1)$$

where z_o = roughness length (assumed to be $0.1\,h$)

h = height of vegetation (or surface clods if bare soil)

d = displacement height ($\simeq 0.63h$)

$L = -u_*^3 . TA . \rho c_p / (kg\,(H + 0.07\lambda E))$

u_* = friction velocity

The wind profile is

$$U(z) = \frac{u_*}{k}\left(\ln\left(\frac{z-d}{z_o}\right) - \psi_M\left(\frac{z-d}{L}\right)\right) \qquad (12.2)$$

where $k = 0.4$

In stable conditions (Webb 1970) $\left(0 < \frac{z-d}{L} < 1\right)$

$$\psi_M\left(\frac{z-d}{L}\right) \simeq -5\left(\frac{z-d-z_o}{L}\right) \qquad (12.3)$$

For $\frac{z-d}{L} > 1$, following Hicks (1976),

$$U(z) = \frac{u_*}{k}\left(\ln(L/z_o) + 5 + \beta \ln\left(\frac{z-d}{L}\right)\right) \qquad (12.4)$$

where $\beta \simeq 6 \quad (1 < \frac{z-d}{L} < 4)$

$\beta \simeq 8 \quad (4 < \frac{z-d}{L})$

In unstable conditions ($L < 0$)

$$\psi_M\left(\frac{z-d}{L}\right) = 2\ln\left(\frac{1+y}{2}\right) + \ln\left(\frac{1+y^2}{2}\right) - 2\tan^{-1}y + \pi/2 \qquad (12.5)$$

where $$y = \left(1 - 16\left(\frac{z-d}{L}\right)\right)^{1/4} \qquad (12.6)$$

Profiles of potential temperature and specific humidity in stable conditions are given by

$$\frac{\theta(z)-\theta(o)}{T_*} = \frac{q(z)-q(o)}{q_*} = \frac{1}{k}\left(\ln\left(\frac{z-d}{z_T}\right) - \psi_H\left(\frac{z-d}{L}\right)\right) \qquad (12.7)$$

where $T_* = -H/\rho c_p u_*$

$q_* = -E/\rho u_*$

$z_T \simeq z_q \simeq 0.2 z_o$

$\psi_H = \psi_M$ (Eq 12.3, 12.4)

In unstable conditions

$$\frac{\theta(z)-\theta(o)}{T_*} = \frac{q(z)-q(o)}{q_*} = \frac{1}{k}\left[\ln\left((1-y_1)/(1+y_1)\right)\right]_{z_T,q}^{z} \qquad (12.8)$$

where $y_1 = y^2$

These equations may be manipulated to give the necessary values of U, T and q at 20 m from measurements at other heights provided H and λE are known. Since these latter are not known some iteration in conjunction with the combination equation is needed to calculate the required values.

The aerodynamic resistance in unstable conditions is

$$r_a = \frac{1}{k^2 U(z)}\left[\ln\left((1-y_1)/(1+y_1)\right)\right]_{z_T}^{z} \cdot \left(\ln\left(\frac{z-d}{z_o}\right) - \psi_M\left(\frac{z-d}{L}\right)\right) \qquad (12.9)$$

The corresponding expression for stable conditions is obtained using either (12.3) or (12.4), with the assumption that $\psi_M = \psi_H = \psi_E$ when $L > 0$. L over the crop may differ significantly from L over the short grass of the instrument enclosure and so they are calculated separately, using the assumption that the partitioning of H and λE is the same over either crop.

13. Computational procedure The various stages of computation which have been outlined are too complicated for operational calculations since a number of linked multiple iterations are involved. The difficulty may be avoided in principle by adopting the procedure outlined by Thompson (1978c) for calculating surface temperature where the results of the accurate computations obtained for full ranges of all the variables are fitted by a "simple" function requiring at most 2 passes with real data to produce the required estimate. The procedure for the present case is to calculate first evapotranspiration for realistic ranges of wind speed, temperature, roughness length, specific humidity deficit, bulk stomatal resistance and available energy using the accurate methods outlined above. The calculation produces also the difference between screen and bulk surface temperature. It is then assumed that available energy has been estimated in the conventional manner from duration of bright sunshine and screen temperature, without an allowance for the possibility of a different surface temperature. This "apparent" available energy is corrected for this difference of temperature and the calculation is repeated to produce a final accurate estimate of evapotranspiration. The value is compared with the approximate estimate obtained using the combination formula assuming first neutral stability and second that wind speed, temperature and vapour pressure deficit are the same at the same height above the instrument enclosure (short grass) and the crop. The final stage is the addition to this latter "simple" combination equation of a correction factor which is a function of the variables involved and which produces accurate estimates of evaporation. This last "corrected" combination formula cannot be calculated in a single pass, for the reasons given in Thompson (1978c).

14. Daytime results in non-advective conditions The computational procedure involved the simultaneous solution of a number of equations, some of which were non-linear, and was performed by a simple method of successive approximations. This procedure worked satisfactorily for those situations where the buoyancy flux was directed upwards, away from the surface, typical of daytime cases in non-advective conditions. The method failed however in nighttime cases or in daytime advective cases, with a downward buoyancy flux, and the results to be presented here exclude these latter cases. The calculations were performed for the following values of the variables:

Available energy (uncorrected for surface temperature)	50, 100, 200, 500 Wm^{-2}
Wind speed at 10 m	2, 5, 10 ms^{-1}
Roughness length	0.01, 0.03, 0.1, 0.3, 1.0 m
Temperature	5, 10, 15, 20, 25 deg C
Specific humidity deficit	.001, .002, .005, .008
Bulk canopy resistance (r_s')	0, 30, 60, 100, 200, 500 sm^{-1}

Table 1 shows a summary of the calculated corrections to available energy to allow for surface heating. Dashes indicate that the atmosphere was stably stratified for the particular variable values. A few small negative values (indicating higher available energy than $R_N - G$ (surface temperature less than screen temperature)) occur because the buoyancy flux includes a contribution from the vertical flux of water vapour as well as from the heat flux. The results in the Table show that for small values of r_s' the atmosphere will be stably stratified unless winds are light, or vapour pressure deficit is very small, or available energy is large. Over rougher surfaces (z_o = 0.1 m, corresponding to the mature cereals) in winds of 5 ms^{-1} inversions will develop over a crop carrying surface water (r_s' = 0) even with vapour pressure deficits as small as 0.001 unless available energy exceeds 200 Wm^{-2}. Over dry, dense, well-watered crops ($r_s' \sim 30$ sm^{-1}) the results show that it is not possible to sustain large vapour pessure deficits over the crop and also experience the usual diurnal (daytime) temperature wave unless available energy is very large or winds are light. Clearly the Table can be used to estimate whether dense vegetation over extensive surfaces was freely transpiring, by comparing vapour pressure deficits and winds measured over the crop with those values which would allow a normal daytime temperature wave to occur.

The main products of the calculations are summarised in Figure 1 which shows the differences between the accurate values of latent heat flux and those derived using the combination formula in the approximate way described in § 13 (assumptions of neutral stability etc). Numbers plotted on the curves are the latter values for $R_N - G$ of 200 Wm^{-2}. At low wind speeds and moderate or large available energy, the accurate values may be as much as 30% smaller than the approximate values when the bulk stomatal resistance is large, demonstrating in part the substantial errors involved in neglecting differences between air and surface temperatures when estimating available energy. At typical daytime temperatures of 15-20 deg C and with moderate specific humidity deficits ($\sim$ 0.005) errors are only a few per cent however for the dense unstressed crop ($r_s' \sim 30$ sm^{-1}). Absolute errors decrease at higher wind speeds and surface roughnesses: largest values for these errors in light winds (U = 2 ms^{-1}), small surface roughness and for $R_N - G$ = 200 Wm^{-2} are around 20 Wm^{-2}.

15. Conclusions It has been shown that substantial errors may occur in estimates of transpiration if these are made by straightforward application of the combination formula, without correction for atmospheric stability and ignoring the effects of surface warming on the available energy. The results presented refer only to occasions with positive buoyancy flux. Attempts to perform similar calculations in nighttime or advective situations with negative buoyancy flux have been unsuccessful so far due to instabilities in the adopted computational procedures. When results are obtained in these latter conditions an attempt will be made to produce a simple algorithm which when used with the simple combination formula yields values of latent heat flux which match closely those produced by the accurate procedures discussed in this paper.

Any comments or suggestions on this paper should be referred to the author.

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APPENDIX An outline of procedures for practical calculations of evapotranspiration

1. Daylength Transpiration from a crop is unlikely to start immediately on sunrise because of negligible stomatal opening at the then low light levels. In practice it may be unnecessary to worry about this because on most clear mornings dew will have to be evaporated initially and by the time that this has been done the light levels will be high enough in most cases to produce significant stomatal opening. On cloudy or overcast days in winter the light levels will be low throughout the day and significant adjustment to bulk stomatal resistance will be required to account for this. The local time of sunrise is determined to some extent by sun radius ($\sim$ 34') and refraction at low elevations ($\sim$ 16'): thus "sunrise" occurs with the sun's centre still 50' below the horizon and so the time of sunrise is

$$t_1 = \frac{12}{\pi} \arccos\left(\tan\delta \tan\phi + \frac{0.0145}{\cos\delta\cos\phi}\right) \qquad (A.1.1)$$

where δ = declination

$$= \frac{23.5}{57.3} \cos\left(\frac{2\pi(d-172)}{365}\right) \qquad (A1.2.)$$

and d = day of year (1 $\equiv$ Jan 1st)

ϕ = latitude

Daylength is given by

$$DAYLEN = 24 - 2.t_1 \qquad (A.1.3)$$

2. Solar constant This varies annually according to the relation (Hughes et al 1977).

$$SOLAR = 1360\left(1 + 0.035 \cos\frac{2\pi d}{365}\right) \quad Wm^{-2} \qquad (A.2.1)$$

3. Radiation flux density at top of atmosphere

$$R_o = SOLAR\left(\sin\delta\sin\phi - \cos\delta\cos\phi\cos\left(\frac{\pi t}{12}\right)\right) \qquad (A.3.1)$$

where t is local time

4. Daytime total of downward radiation at top of atmosphere

$$ROTOT = 3600 \int_{t_1}^{24-t_1} R_o \, dt$$

$$= 3600.\,SOLAR\left(\sin\delta\sin\phi.\,DAYLEN + \frac{24}{\pi}\cos\delta\cos\phi\sin\left(\frac{\pi t_1}{12}\right)\right) \quad Jm^{-2} \qquad (A.4.1)$$

5. (Daytime)total of net solar radiation at surface

$$RNS = ROTOT(1-\alpha)\left(e(a+bn/N) + (1-e)c\right) \qquad (A.5.1)$$

where α = albedo ($\simeq$ 0.25 for fairly short green crops)

n = number of hours of bright sunshine

N = maximum number of hours of sunshine as calculated by Eq (A.1.1)

$a \simeq 0.24$
$b \simeq 0.50$
$c \simeq 0.15$

Cowley (1978) shows how these quantities vary (slightly) with location: b is also found to vary with season.

$e = 0$ if $n = 0$

$= 1$ if $n > 0$

6. Net long wave radiation (clear skies) The sky component of flux density is given by (Swinbank 1963)

$$RLDOWN = -113 + 1.03\sigma(Tk)^4 \qquad Wm^{-2} \qquad (A.6.1)$$

where

Tk = air temperature (deg K)

$\sigma = 5.67 \times 10^{-8}\ Wm^{-2}\ (^{o}K)^{-4}$

The ground (upward) component is

$$RLUP = \sigma (Tk_s)^4 (1 - \alpha_L) \qquad (A.6.2)$$

where Tk_s = surface temperature (deg K)

$1 - \alpha_L$ = surface emissivity ($\simeq 0.95$)

After allowance for reflection of some of the sky component the net long wave radiation is

$$RLN = (1-\alpha_L)(-113 + \sigma (1.03(Tk)^4 - (Tk_s)^4) \qquad (A.6.3)$$

The total daytime long wave radiation for a cloudy atmosphere is

$$RLNDAY = 3600.\ RLN\ (0.1 + 0.9n/N).\ DAYLEN \qquad (A.6.4)$$

Nighttime radiation is

$$RLNITE = 7200\ RLN\ (0.1 + 0.9n/N).\ t_1 \qquad (A.6.5)$$

Pending further studies it will be assumed that day and nighttime air temperatures are both given by

$$TA = 0.5\ (TA(MAX) + TA(MIN)) \qquad (A.6.6)$$

7. Soil heat flux Total daytime flux of heat into ground is

$$GDAY = G1 \left(\frac{22 - t_1}{24 - t_1}\right) \qquad (A.7.1)$$

where

$$G1 = 0.4\,(RLNDAY + RNS)(1 + 0.4\,LAI)^{-1} \qquad (A.7.2)$$

Nighttime case:-

$$GNIGHT = \begin{cases} 0.5.\,RLNITE & \text{(soil dry)} \\ 0.8.\,RLNITE & \text{(soil wet)} \end{cases} \qquad (A.7.3)$$

"Soil wet" applies to any recently re-wetted soil in which soil moisture deficit in the surface layer is less than (15, 10, 5 mm) (for heavy, medium, light soil). "Soil dry" is used when these deficits are exceeded for the surface layer and when there has been no recent rain.

8. Available energy

Daytime:-

$$RDAY = RLNDAY + RNS - GDAY \qquad (A.8.1)$$

Nighttime:-

$$RNITE = RLNITE - GNIGHT \qquad (A.8.2)$$

9. Saturation specific humidity

$$q(sat) = 0.00062 \exp\left(19.0785 - 4098.03/(T + 237.3)\right) \qquad (A.9.1)$$

where T is in deg C

10. Variation of saturation specific humidity with temperature (Δ')

$$\Delta' = \left(2.54/(T + 237.3)^2\right) \exp\left(19.0785 - 4098.03/(T + 237.3)\right) \qquad (A.10.1)$$

11. c_p , λ and ρ

$$c_p = 1005 \text{ J Kg}^{-1} \text{ K}^{-1} \qquad (A.11.1)$$

$$\lambda = 2.465 \times 10^6 \text{ J Kg}^{-1} \qquad (A.11.2)$$

$$\rho \simeq 1.29\,(273/(273 + TA))(1 - 1.2\,h \times 10^{-4}) \qquad (A.11.3)$$

where h is height above sea level.

Table 1 Reduction in available energy (Wm^{-2}) due to surface heating (pairs of values are for 2 and 5 ms^{-1} respectively)

$R_N - G$	δq	$r_s' = 0$	30	60	100	200	500
			Zo = 0.01m,	T = 15 deg C			
50	.001	4/0	5/1	6/3	7/4	9/5	11/7
	.002	0/-	2/-	3/0	4/1	6/4	10/6
	.005	-/-	-/-	-/-	-/-	1/-	7/4
	.008	-/-	-/-	-/-	-/-	-/-	3/1
100	.001	10/3	12/6	14/8	15/9	18/12	22/15
	.002	6/-1	9/3	11/5	13/7	16/10	21/14
	.005	-/-	0/-	2/-	5/0	11/6	18/11
	.008	-/-	-/-	-/-	-2/-	5/1	15/9
200	.001	20/10	24/15	27/18	30/20	35/24	42/29
	.002	17/6	21/11	24/15	28/18	34/23	41/28
	.005	7/-	12/2	16/7	21/12	28/18	38/26
	.008	-2/-	4/-	9/-1	14/5	23/14	35/23
500	.001	46/28	54/37	61/44	68/50	80/59	95/68
	.002	43/24	52/34	59/41	66/48	78/57	94/67
	.005	33/13	43/26	51/34	60/42	73/53	91/65
	.008	24/2	35/17	44/27	53/36	69/49	89/63
			Zo = 0.1m,	T = 15 deg C			
50	.001	-1/-	1/-	3/1	4/2	5/3	7/3
	.002	-/-	-/-	0/-	1/0	4/2	6/3
	.005	-/-	-/-	-/-	-/-	-/-	3/2
	.008	-/-	-/-	-/-	-/-	-/-	1/0
100	.001	3/-	5/2	7/4	9/5	11/6	13/7
	.002	-1/-	2/-	5/1	7/3	9/5	12/6
	.005	-/-	-/-	-/-	0/-	5/2	10/6
	.008	-/-	-/-	-/-	-/-	1/-	9/4
200	.001	9/2	13/7	15/10	18/11	21/13	24/15
	.002	5/-	10/4	13/7	16/10	20/12	23/15
	.005	-/-	1/-	6/1	10/5	16/9	22/13
	.008	-/-	-/-	-1/-	4/-	12/7	19/12
500	.001	22/11	31/21	36/26	41/29	47/33	52/36
	.002	18/7	28/18	34/24	39/28	45/32	51/36
	.005	9/-	20/10	28/18	34/23	42/30	50/35
	.008	0/-	12/2	21/12	29/19	39/27	48/33
			Zo = 0.01m,	T = 5 deg C			
100	.001	11/4	13/7	15/9	17/10	19/12	22/14
	.005	-/-	0/-	3/-	6/0	11/6	18/11
			Zo = 0.01m,	T = 25 Deg C			
100	.001	8/3	10/5	12/7	13/9	17/11	22/15
	.005	-3/-	0/-	2/-	5/0	10/5	17/11
			Zo = 0.1m,	T = 5 deg C			
100	.001	3/-	6/2	8/4	9/5	11/6	12/7
	.005	-/-	-/-	-/-	0/-	5/2	10/5
			Zo = 0.1m,	T = 25 deg C			
100	.001	2/-	5/2	6/5	8/5	11/6	13/8
	.005	-/-	-/-	-/-	0/-	5/2	11/6

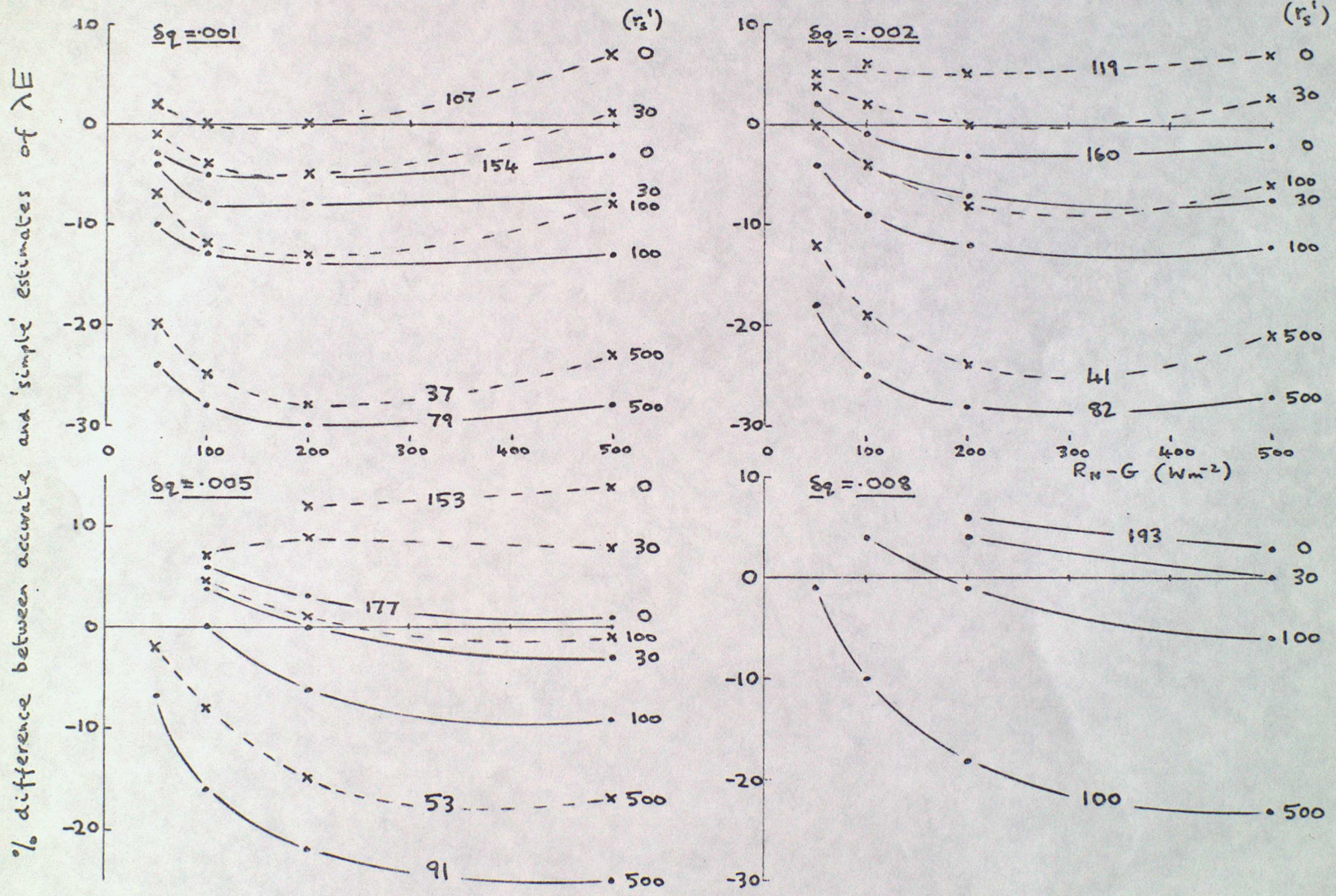

Figure 1(a) $z_0 = 0.01$ m $U = 2 ms^{-1}$ (x---x 5 deg C: •——• 25 deg C)

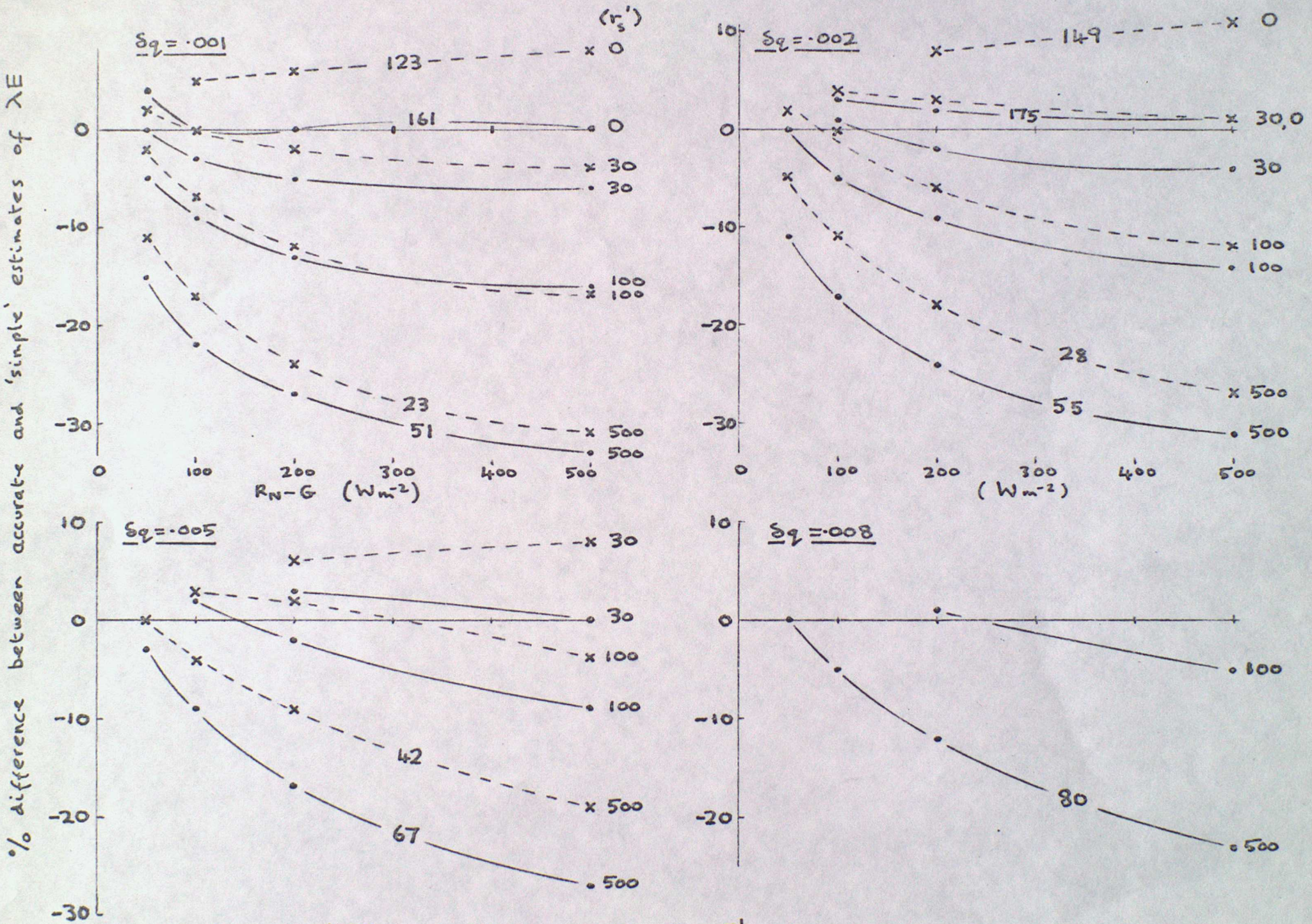

Figure 1 (b) $z_0 = 0.1m$ $U = 2\ ms^{-1}$

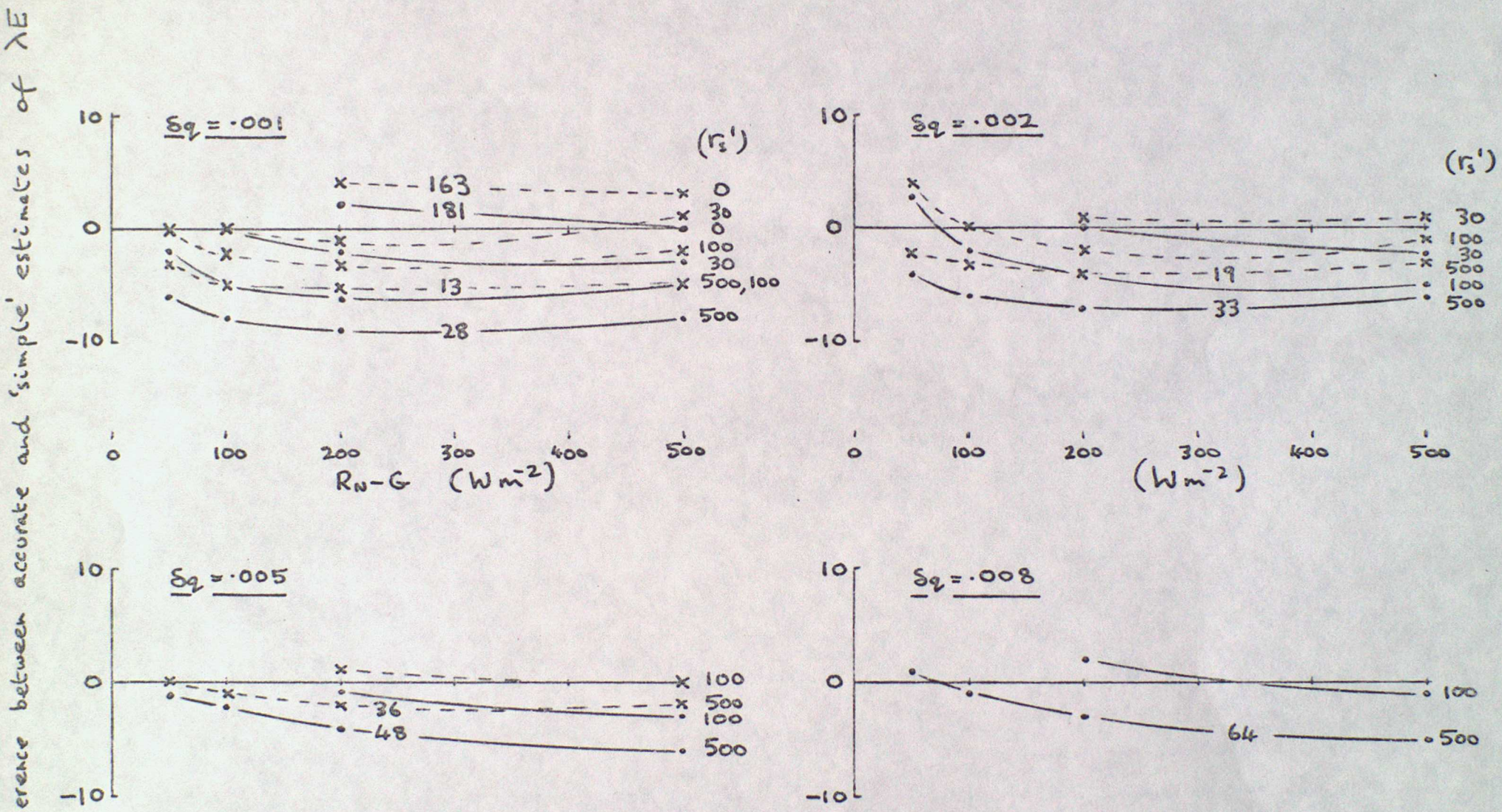

Figure 1 (d) $z_o = 0.10m$ $U = 5 m s^{-1}$

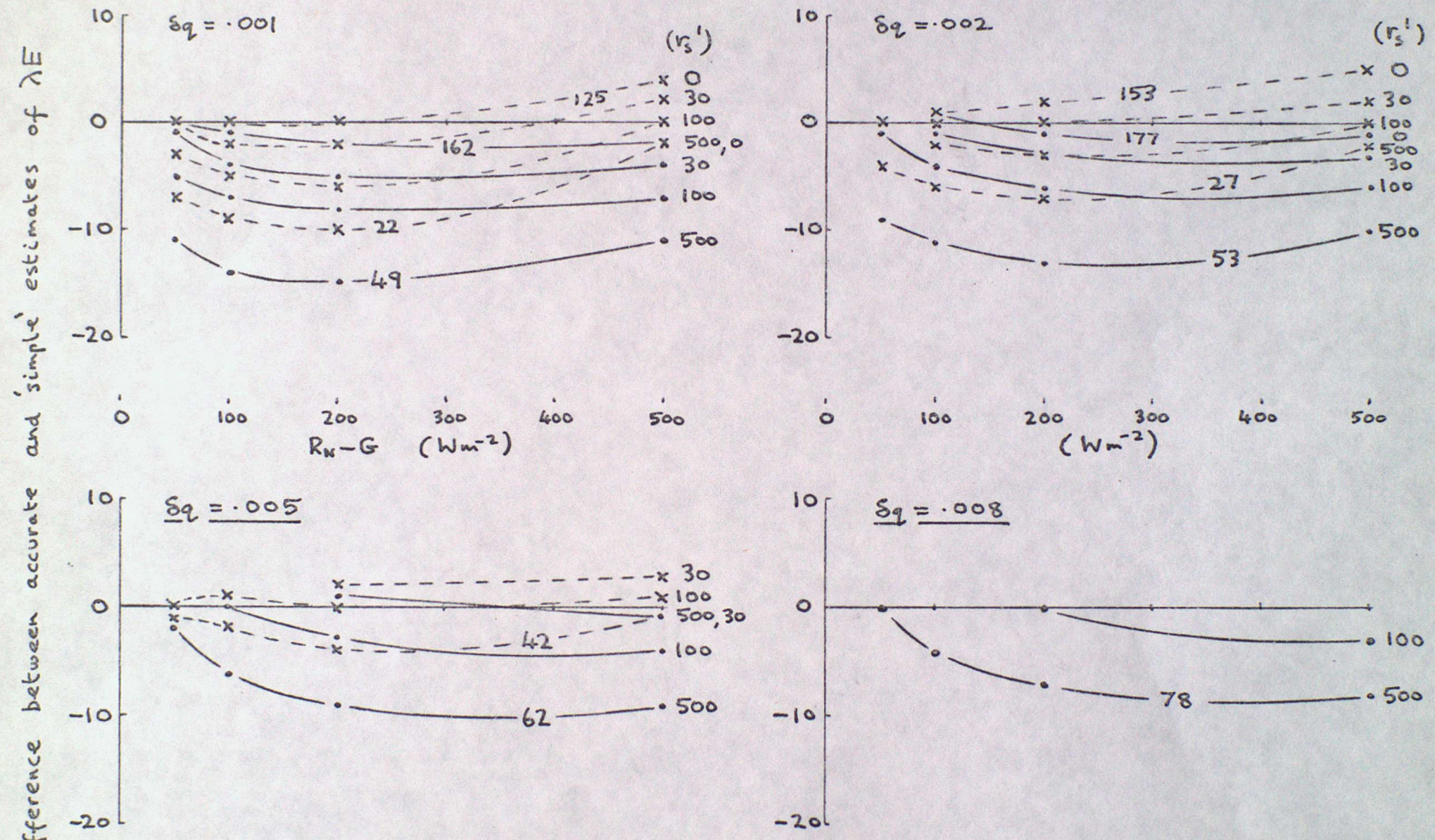

Figure 1(c) $z_0 = 0.01$ m $U = 5 ms^{-1}$